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DARK MATTER ANNIHILATION IN THE UNIVERSE

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The astronomical dark matter is an essential component of the Universe and yet its nature is still unresolved. It could be made of neutral and massive elementary particles which are their own antimatter partners. These dark matter species undergo mutual annihilations whose effects are briefly reviewed in this article. Dark matter annihilation plays a key role at early times as it sets the relic abundance of the particles once they have decoupled from the primordial plasma. A weak annihilation cross section naturally leads to a cosmological abundance in agreement with observations. Dark matter species subsequently annihilate – or decay – during Big Bang nucleosynthesis and could play havoc with the light element abundances unless they offer a possible solution to the ${}^7\text{Li}$ problem. They could also reionize the intergalactic medium after recombination and leave visible imprints in the cosmic microwave background. But one of the most exciting aspects of the question lies in the possibility to indirectly detect the dark matter species through the rare antimatter particles – antiprotons, positrons and antideuterons – which they produce as they currently annihilate inside the galactic halo. Finally, the effects of dark matter annihilation on stars is discussed.

Keywords: dark matter, Big Bang nucleosynthesis, cosmic rays, stellar evolution

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1. Dark Matter production through annihilation

Large amounts of invisible matter in the Universe have been discovered in 1933 when the Swiss astronomer Fritz Zwicky measured ¹ the velocity dispersion of individual galaxies inside the Coma cluster. That self-gravitating system contains thousands of objects and has quite certainly virialized given its age and spherical shape. Because a steady state has been reached, the cluster mass and size can be related to the velocity dispersion of the galaxies which it shelters. Zwicky determined for the first time the dynamical mass of the Coma cluster and obtained a value more than a hundred times larger than the visible counterpart inferred from the luminosity of

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galaxies. The astronomical dark matter puzzle originates from this measurement. Since then, it has been continuously confirmed by an impressive series of refined observations performed with quite different methods. The analysis of the X-ray emission from the hot gas filling clusters allows to reconstruct their gravitational potential wells and to infer their dynamical mass. The weak and strong lensing of distant sources can also be used to derive the amount of material bending the light trajectories. The dynamical to visible mass ratio is always very large. Clusters can be pictured as icebergs with a tiny emerged visible part and a by far dominant hidden component made of dark matter (DM).

The problem also exists on galactic scales as demonstrated by Vera Rubin² and Albert Bosma³ in 1979. The rotation curves of spirals are determined with the help of the Doppler effect through the 21 cm line emission from orbiting clouds of neutral atomic hydrogen HI. The rotation speed of the disk does not exhibit the Keplerian decrease which would be typical of a central and dominating mass. On the contrary, it is found to remain flat far beyond the optical radius. The dynamical mass of spirals does not lie therefore in their bulges but is spread over an extended halo of unseen material.

More recently, the measurements of the cosmic microwave background (CMB) anisotropies by the Planck satellite in 2013 provide clear evidence⁴ for a flat universe whose density $\Omega_{\text{tot}} = 1$ is equal to the closure value. A fluid with negative pressure, dubbed dark energy or quintessence, coexists with non-relativistic matter. Dark energy contributes a fraction $\Omega_{\Lambda} = 0.6825$ to the total mass budget whereas matter amounts to $\Omega_{\text{M}} = 0.3175$. Nucleons and electrons which make up the so-called baryonic matter contribute only a small fraction $\Omega_{\text{B}} = 0.049$ in agreement with primordial nucleosynthesis. A dark component with density $\Omega_{\text{DM}} = \Omega_{\text{M}} - \Omega_{\text{B}} = 0.2685$ appears on cosmological scales with the surprising property of being made of an unknown form of matter.

Theoreticians have been imagining for the last three decades a plethora of candidates for this astronomical dark matter. In spite of the proliferation of more or less exotic models, the interest of the community has focused on the supersymmetric or Kaluza-Klein extensions of the standard model of particle physics. These theories are based on a new symmetry of Nature and naturally predict the existence of a weakly interacting and massive particle – dubbed WIMP – whose mass lies in the GeV to TeV range with typically weak interactions. This species is moreover stable because of the conservation of the quantum number associated to the new symmetry. It is electrically neutral and is its own anti-particle. A WIMP pair can annihilate to produce standard particles like fermions or gauge bosons.

$$\chi + \chi \rightleftharpoons f + \bar{f}, W^+ + W^-, Z^0 + Z^0, \dots \quad (1)$$

Dark matter annihilation plays a crucial role in the early Universe as it provides a natural mechanism through which WIMPs have been produced. Because reaction (1) is in equilibrium during the Big Bang, DM species exist under the form of an ultra-relativistic radiation as long as the temperature of the primordial plasma

exceeds their mass. For a 10 GeV particle, this happens before an age of a few ns. As soon as this condition stops to be fulfilled, WIMPs annihilate without being produced back from lighter particles. Their density drops significantly until they are so diluted that they stop interacting with each other. This chemical quenching leaves a steady population of particles whose density decreases as space expands. Because they are stable, WIMPs contribute today to the mass budget of the Universe. Actually, their cosmological relic abundance is found ⁵ to depend only on the annihilation cross section with

$$\Omega_\chi h^2 = \frac{3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{\text{an}} v \rangle}, \quad (2)$$

where h is the Hubble constant. With a cross section $\langle \sigma_{\text{an}} v \rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ typical of weak interactions, the cosmological abundance Ω_χ falls naturally close to the observed value of $\Omega_{\text{DM}} \simeq 0.27$. This coincidence is called the WIMP miracle and is the reason why this type of particle is considered as the favoured candidate to the astronomical dark matter.

2. Dark Matter Annihilation and Big Bang Nucleosynthesis

Big Bang nucleosynthesis (BBN) is in remarkable agreement with observations of light element abundances although some tension exists for ${}^7\text{Li}$. That species is essentially produced through ${}^4\text{He} + {}^3\text{He} \rightarrow {}^7\text{Be} + \gamma$ with subsequent electron capture of ${}^7\text{Be}$ into ${}^7\text{Li}$. The BBN theory predicts an abundance of ${}^7\text{Li}/\text{H} = 5.24^{+0.71}_{-0.67} \times 10^{-10}$ whereas a plateau – the so-called Spite plateau – is measured at a level of ${}^7\text{Li}/\text{H} = 1 - 2 \times 10^{-10}$ regardless of the metallicity. Moreover, in standard BBN, the ${}^6\text{Li}$ isotope is formed in the reaction ${}^4\text{He} + \text{D} \rightarrow {}^6\text{Li} + \gamma$ which is extremely inefficient, hence a theoretical value of ${}^6\text{Li}/\text{H} \sim 10^{-14}$. Significant traces of that element have nevertheless been found in the low-metallicity halo star HD84937 for which ${}^6\text{Li}/{}^7\text{Li} = 0.052 \pm 0.019$.

Primordial nucleosynthesis can be significantly perturbed by the injection of energetic and non-thermal particles produced by the residual annihilation or decay of WIMPs. DM species could play havoc with the synthesis of light elements in many ways ⁶. To commence, electromagnetic products – electrons, positrons and photons – generate showers and can lead to the photodissociation of nuclei. Photons injected in the primordial plasma generate electromagnetic showers as long as their energy E_γ exceeds the threshold energy $E_C \simeq m_e^2/22T$ for pair production on the CMB. That process is dominant because the baryon-to-photon ratio is so small. Alternatively, shower photons with $E_\gamma \leq E_C$ can pair produce on protons and ${}^4\text{He}$ nuclei. They also Compton scatter off plasma electrons. They have finally a small chance to photodisintegrate D below 3 keV and later on ${}^4\text{He}$ below 0.3 keV. Nuclei can be destroyed as soon as the cut-off energy E_C exceeds their photodissociation threshold. The larger the latter, the smaller the temperature at which destruction starts to take place. The dissociation of ${}^4\text{He}$ produces D and ${}^3\text{He}$ and leads to an abnormally large ${}^3\text{He}/\text{D}$ ratio.

WIMP annihilation or decay can also produce hadronic particles. Injection of π^\pm induces charge exchange reactions $\pi^- + p \rightarrow \pi^0 + n$ for temperatures between 1 MeV and 300 keV. Creation of extra neutrons after the neutron-to-proton ratio n/p freeze-out implies an increase of the helium mass fraction Y_p . The same effect occurs if antinucleons are injected in the primordial plasma since they preferentially annihilate on protons, thereby raising the effective n/p ratio. Any extra neutrons injected at $T \sim 40$ keV can lead to an important depletion of ${}^7\text{Be}$. Depending on its magnitude, this mechanism could solve the lithium problem. Finally, at lower temperatures, energetic neutrons and protons can destroy ${}^4\text{He}$ through $n + {}^4\text{He} \rightarrow {}^3\text{H}$ (${}^3\text{He}$) + p (n) + n + (π 's) or $n + {}^4\text{He} \rightarrow \text{D} + p + 2n$ + (π 's). This can result in the overproduction of D but may also lead to a much larger ${}^6\text{Li}$ abundance than predicted by standard BBN.

Non-thermal BBN provides a framework to solve the ${}^7\text{Li}$ problem. If a small admixture of neutrons is injected by WIMP annihilation or decay during or just after the synthesis of ${}^7\text{Be}$, *i.e.*, for temperatures between 60 and 30 keV, this element is converted into ${}^7\text{Li}$ via the neutron capture $n + {}^7\text{Be} \rightarrow p + {}^7\text{Li}$ and is efficiently destroyed by protons through $p + {}^7\text{Li} \rightarrow {}^4\text{He} + {}^4\text{He}$. This sequence of reactions leads to the depletion of ${}^7\text{Be}$ which is no longer transmuted into ${}^7\text{Li}$ at later times by electron capture, hence a residual ${}^7\text{Li}$ abundance closer to the Spite plateau. That scenario is nevertheless constrained by the requirement that extra neutrons should not overproduce D.

Energetic ${}^3\text{He}$ and ${}^3\text{H}$ may be produced via the spallation (hadronic) or photodissociation (electromagnetic) reactions mentioned above. These nuclei collide on ${}^4\text{He}$ to produce ${}^6\text{Li}$ through the endothermic reactions ${}^3\text{H} + {}^4\text{He} \rightarrow {}^6\text{Li} + n$ - 4.78 MeV and ${}^3\text{He} + {}^4\text{He} \rightarrow {}^6\text{Li} + p$ - 4.02 MeV. For projectiles with energy ~ 10 MeV, the cross sections for these reactions are 10^7 times larger than the cross section of the ${}^4\text{He} + \text{D} \rightarrow {}^6\text{Li} + \gamma$ standard ${}^6\text{Li}$ production mechanism. This opens the possibility for a much larger amount of ${}^6\text{Li}$ than previously anticipated and could explain the observations of the star HD84937. Conversely, ${}^6\text{Li}$ is a sensitive probe of DM annihilation. The cross section for WIMPs annihilating into $q\bar{q}$ pairs is constrained⁶ to be smaller than $8 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1} (m_\chi/100 \text{ GeV})^2$ – where m_χ is the WIMP mass – under the penalty of yielding a ${}^6\text{Li}/{}^7\text{Li}$ ratio in excess of 0.1.

3. Cosmic Microwave Background Constraints

Recombination of the primordial plasma takes place at a redshift $z \simeq 1090$. The electron fraction drops at a level of 10^{-4} and the intergalactic medium (IGM) becomes neutral. Residual WIMP annihilation taking place at that time can perturb the ionization history of the IGM and leave visible imprints on the CMB. Measurements of the CMB temperature and polarization angular power spectra set constraints on the energy deposited in the IGM just after recombination, thereby probing DM annihilation occurring during that epoch.

WIMPs annihilate to a wide range of particles. However, the heating and ioniza-

tion of the IGM result mainly from the injection of electrons, positrons and photons which trigger electromagnetic showers and eventually thermalize with the ambient medium. As shown in 7, the cooling of photons injected at a redshift $z = 1000$ proceeds through various reactions. As the photon energy increases, the dominant mechanisms are photoionization of IGM atoms, Compton scattering off electrons, pair production on the H/He gas, photon-photon scattering and pair production on the CMB. All these processes have timescales much smaller than the Hubble time so that thermalization effectively occurs.

The CMB constraints on possible modifications of the IGM ionization history after recombination translate ^{8,7} into an upper limit of $\sim 4 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ ($m_\chi/100 \text{ GeV}$) on the cross section of WIMPs annihilating into electromagnetic species. This value compares to the BBN bound mentioned previously in the case of a pure $q\bar{q}$ channel. Notice that most of the WIMP models which account for the cosmic ray positron excess discussed in the next section are about to be ruled out by this CMB limit. The Planck satellite will soon be able to set a more stringent bound and could exclude all these models.

4. Indirect Signatures of Dark Matter Species

Should WIMPs pervade the halo of the Milky Way, their mutual annihilations would yield several indirect signatures. Although DM annihilation proceeds now at a very small pace, it may nevertheless lead to the production of high-energy photons and of rare antimatter particles such as antiprotons \bar{p} , positrons e^+ or even antideuterons \bar{D} through the reaction

$$\chi + \chi \rightarrow q + \bar{q}, W^+ + W^-, \dots \rightarrow \bar{p}, \bar{D}, e^+ \gamma \text{ \& } \nu \text{ .} \quad (3)$$

Antimatter species are already manufactured by conventional astrophysical processes. The dominant mechanism is the spallation of primary cosmic ray (CR) protons and helium nuclei on the gas of the galactic plane. Positrons could also be accelerated by nearby highly-magnetized neutron stars called pulsars. The messengers of DM annihilation would generate distortions in the signals detected at the Earth or would appear in the γ -ray sky as hot spots with no optical counterpart – see the review 9 for more details.

Background antiprotons are produced inside the Galactic disk by the collisions undergone by primary CR nuclei on H/He . Because they are not directly injected in the interstellar medium (ISM) but are sourced by primary CR species, these astrophysical antiprotons are dubbed secondaries. In addition to this conventional mechanism, a primary component can be directly produced by DM annihilation all over the Galaxy. Irrespective of the production mechanism, antiprotons propagate inside the magnetic fields of the Milky Way like any charged CR particle. Their transport may be modeled as a diffusion process taking place inside a confinement domain called the magnetic halo. The value of the diffusion coefficient, its dependence on the CR rigidity and the strength of the convective wind that blows the

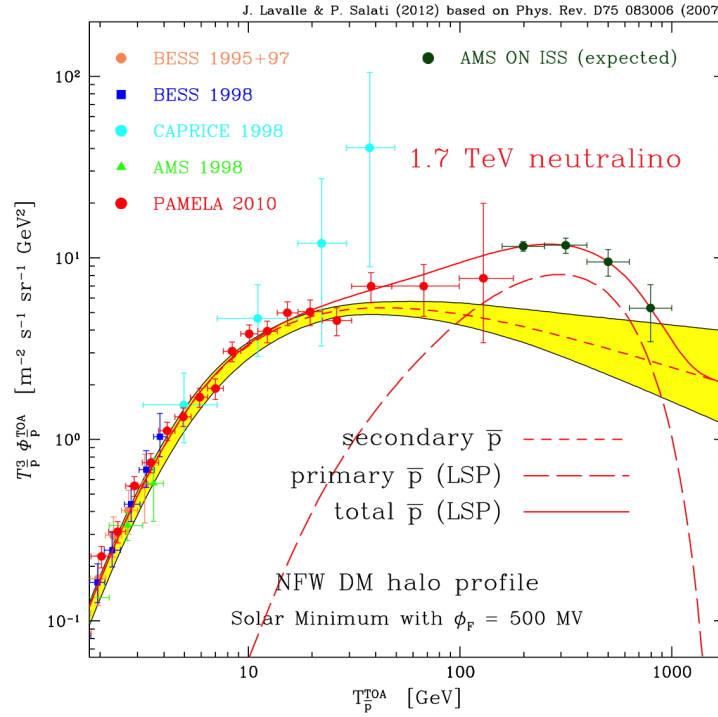


Fig. 1. The yellow band features the expected antiproton background for the full range of diffusion parameters allowed by the B/C ratio. A heavy WIMP is also considered. This DM species is almost a pure Wino and its annihilation cross section is significantly enhanced today by non-perturbative, binding energy effects. The corresponding primary (long dashed) and total (solid) fluxes have been derived for a NFW halo profile and for the set of diffusion parameters that best fits the B/C ratio. For illustration, a global boost factor of 2 has also been included in the signal. The antiproton flux is compared to several measurements, whereas the expected statistical error after 3 years of data sampling by AMS-02 is indicated.

particles away from the disk are unknown parameters which can be constrained from the typical secondary-to-primary B/C ratio. Although these constraints are far from being stringent, the flux of background antiprotons is fairly well determined¹⁰ as featured by the yellow band of Fig. 1. Boron nuclei and secondary antiprotons are produced within the disk from primaries interacting with the ISM. The similarity of the production mechanisms translates into a tight relation between the B/C and \bar{p}/p ratios, hence a good precision on the antiproton background. This is not the case for antiprotons produced by DM annihilation. This process takes place all over the Galaxy and is not confined in its disk. The corresponding flux depends sensitively on the thickness of the CR magnetic halo and is subject to an uncertainty which can reach two orders of magnitude. The DM halo profile is also unknown but the resulting error amounts to a factor ~ 2 once the DM density ρ_\odot in the solar neighborhood is fixed.

The announcement of a positron excess by the PAMELA collaboration¹¹ in

2008 has triggered a lot of excitement. This excess was actually considered as the first hint of the presence of WIMPs in the Milky Way halo. Five years later, the dust has settled down and most of the initial hope has faded away. As is clear from the AMS-02 measurements¹², the anomaly extends up to 300 GeV and points towards a massive species, in good agreement with theoretical expectations. Remember that if WIMPs are thermally produced during the Big Bang, their relic abundance matches the Planck value⁴ of $\Omega_\chi \simeq 0.27$ provided that their annihilation cross section, at the time of decoupling, is equal to $\langle \sigma_{\text{an}} v \rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. Moreover, high-energy positrons cannot diffuse on long distances, and those detected at the Earth must have been produced locally, hence a DM density of $\rho_\odot = 0.3 \text{ GeV cm}^{-3}$. Baring in mind these benchmark values, one finds that the signal at the Earth is way too small to account for the observed excess. For a WIMP mass m_χ of 1 TeV, the positron production rate needs to be enhanced by a factor of $\sim 10^3$ to match the measurements. Another difficulty lies in the absence of an antiproton excess. DM particles cannot couple to quarks under the penalty of overproducing antiprotons^{13,14}. Therefore, besides an abnormally large annihilation rate today, WIMPs should preferentially annihilate into charged leptons, a feature which is unusual in supersymmetry. The positron excess is presumably produced by nearby pulsars.

5. Dark Matter Annihilation and Stellar Evolution

DM particles could play a role in stellar evolution. They may be captured by the stars which they happen to cross as they wander in the Galaxy. WIMPs have a non-vanishing chance to collide on a nucleus inside stellar interiors and to lose enough energy to become gravitationally bound. A population of DM species builds up as time passes on and concentrates at the stellar cores. Because WIMPs interact weakly with their surroundings, they can transport heat on large distances with a better efficiency than radiative diffusion. The central temperature gradient is lowered. This scenario has actually been proposed¹⁵ in 1985 to solve the solar neutrino puzzle. But DM annihilation is a counteracting process that limits the growth of the WIMP density. Once taken into account, the WIMP explanation of the solar neutrino puzzle is no longer tenable.

In 1989, the focus was on DM annihilation inside stars. If DM haloes form from an initial spherical configuration, they collapse into a central spike where the WIMP density can be extremely large. This could be the case at the Galactic center. A star floating in this environment would capture WIMPs at such a pace that DM annihilation inside the object would provide enough energy to perturb the stellar evolution. As shown in 16, main sequence stars would become red giants and would be shifted in the H-R diagram towards the Hayashi track. But these effects occur for large WIMP capture rates and require a WIMP-nucleus scattering cross section of order 1 picobarn. Direct detection experiments have set very stringent upper limits on that cross section and the scenario faded away.

The idea that WIMPs can significantly alter stellar evolution was revived in 2007. During the dark age, at a redshift z between 10 and 50, DM is much denser than today, especially at the centers of DM proto-haloes. These substructures act as potential wells inside which baryons collapse as soon as molecular hydrogen becomes sufficiently abundant to allow efficient gas cooling. The first generation of stars, *i.e.*, the so-called population III, starts shining. The scenario proposed by 17 is based on the backreaction of the collapsing gas cloud on the surrounding DM distribution. Adiabatic contraction drags WIMPs inwards as the gas concentrates and heats up. Eventually, a dark star is born powered by the annihilation of the DM species which it contains. The object is much cooler and more extended than standard Pop III stars. The surface temperature does not exceed 2×10^4 K, hence a very weak UV emission. The surrounding gas is not ionized and can cool down, thereby falling on the dark star which it feeds with more gas and more WIMPs. The stellar mass increases up to $\sim 800 M_\odot$ or even beyond¹⁸. Eventually, DM annihilation is no longer able to power the star which contracts into a very massive object powered by nuclear fusion. Its mass is so large that it may end its life as a hypernova. Dark stars could be detected in the infrared with the James Webb space telescope pointing through the central regions of foreground galaxy clusters acting as gravitational lenses.

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